THE EFFECTS OF REFORESTATION ON TEMPERATURE IN THE SOUTHEAST UNITED STATES

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

The Effects of Reforestation on Temperature in the Southeast United States. (May 2015)

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The Southeast United States has experienced suppressed warming compared with the rest of the country since the early part of the 20th century. This region has also undergone drastic land use/land cover changes – from depleted farmland in the 1920s to flourishing forest landscape in the 1960s. This study investigates reforestation in the Southeast U.S. as a probable influence on the Southeast “warming hole.” The region used encompasses the naturally forested areas of the southeastern U.S. and includes the portion of the Southeast that has experienced suppressed warming; the states or parts of states used are: Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, and East Texas. Historical forestland cover and temperature data for summer and winter seasons for the decades of the 1930s, 1960s, and 1990s were used. The decadal mean minimum and maximum temperature departures from normal are calculated for long-term stations with nearly-complete records. The decades are compared by plotting their reforestation fraction against their temperature change for June-August (JJA) maximum and minimum temperatures and December-February (DJF) maximum and minimum temperatures. The results showed that the 1930s-1960s was a time of cooling and experienced more cooling with more reforestation, and that the 1960s-1990s was a time of warming with no apparent reforestation effect. Statewide analyses were

executed for summer and winter maximum and minimum temperatures as well. The minimum temperatures showed a stronger effect than its maximum counterpart, regardless of the time period. Overall, a majority of the states experienced more cooling (less warming) with more reforestation and less cooling (more warming) with less reforestation in most cases.

CHAPTER I

INTRODUCTION

Warming hole.

Since the early part of the 20th century, many parts of the Southeast U.S. have experienced a cooling anomaly. When comparing with the national average temperature trends from the 1900s to the 2000s, the southeastern U.S. has experienced less warming during 'warming periods' and more cooling during 'cooling periods' (Kennedy), as illustrated in Figure 2. The exact cause of this "warming hole," as scientists have dubbed it, is unclear. It is unlikely that there is a single cause; there are many factors that could contribute to this trend, one being land cover/land use change.

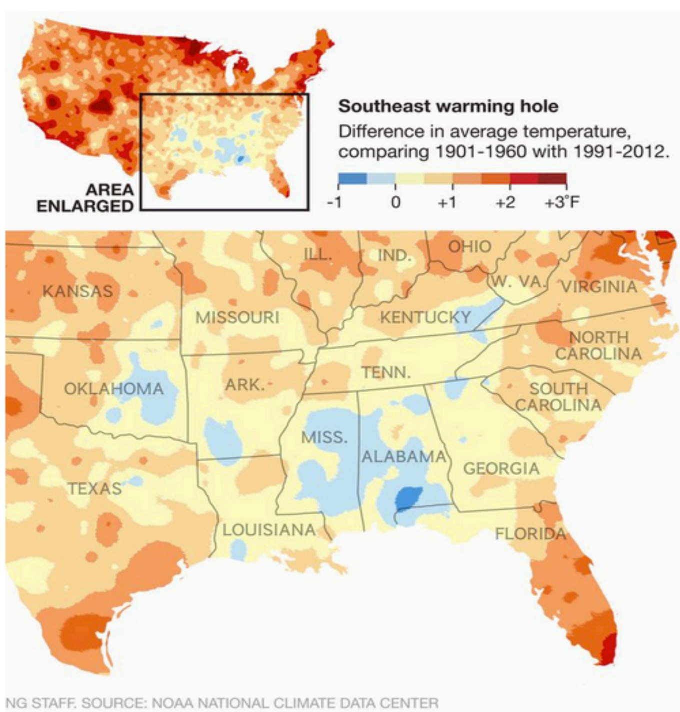

Figure 1. Southeast U.S. Warming Hole. Difference in the average temperatures in the U.S. Taken by comparing 1901-1960 with 1991-2012. Obtained from NOAA National Climate Data Center.

The Southeast "warming hole" is evident in Figure 1, which illustrates the dramatic difference between the southeastern U.S. compared with the rest of the country. The image compares the difference in average temperatures of 1901-1960 to 1991-2012.

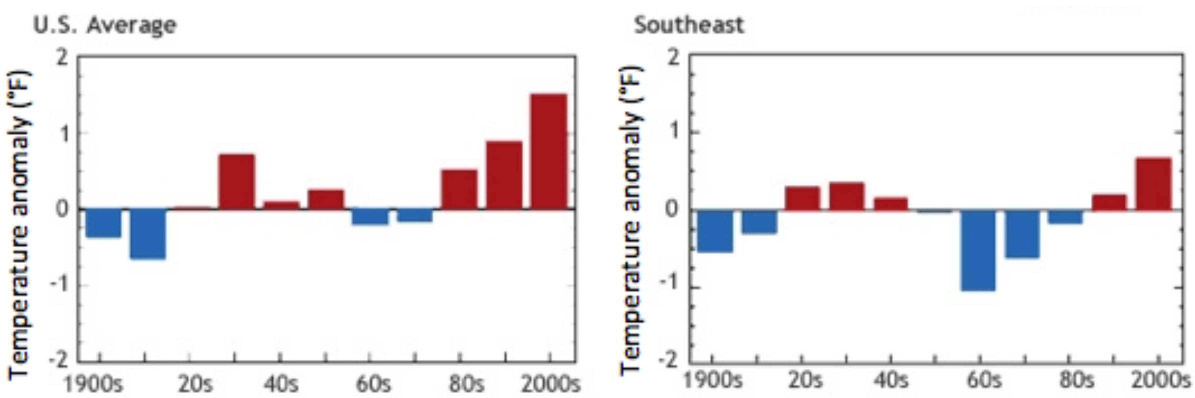

Figure 2. Temperature Anomalies by Decade. The bars on the graph show the average temperature anomalies by decade for 1901-2012 (relative to the 1901-1960 average) for each region. Obtained from NOAA NCDC/CICS-NC

Figure 2 shows the 1901-2012 temperature anomalies relative to the 1901-1960 average for the U.S. and the Southeast. It is clear that when the U.S. average was above normal (red bars), the changes were less dramatic for the Southeast; and when the U.S. average was below normal (blue bars), these changes were generally more enhanced for the Southeast. This suggests that the Southeast has a weaker warming anomaly and a stronger cooling anomaly.

The Southeast is a region that is strongly influenced by the Atlantic subtropical high and the Gulf of Mexico. The Bermuda High is a major contributor to the heat waves, droughts, and hurricanes that the region experiences. The Gulf of Mexico is a moisture source that influences the area's precipitation events (Powell). Increased precipitation leads to wetter soils and increased evapotranspiration, lowering daytime temperatures. With this in mind, studies have looked to see how precipitation amounts in the Southeast have changed over the time period and seen if there is a significant relationship between the two factors. Powell and Keim et. al 2015 looked at trends in daily temperature and precipitation extremes in the Southeast U.S. as one possibility of this warming hole. They found that from 1948-2012 the majority of stations in the Southeast experienced downward trends in extreme maximum temperatures and an upward trend in extreme minimum temperatures. The downward trend in maximum temperatures is consistent with the results of the warming hole. They also found that the Southeast experienced significantly more extreme precipitation, with the precipitation events becoming more efficient and intense across the region.

Other explanations that may be causing the warming hole include: the seasonal variability of the Bermuda High (BH), which has a strong effect on temperature and precipitation in the region (Powell); El Nino and La Nina oscillations (ENSO) (Powell); changes in dewpoint temperatures and humidity – increases in both of these would lead to lower surface temperatures (Brown), but this may also be related to the BH, ENSO, and the moisture-laden Gulf of Mexico; air pollution of sulfates, which cause cooling by scattering and reflecting light (Voiland); and what this study focuses on, land use and land cover changes (Trail).

Historical Vegetation Change.

The Southeast is a region marked by historical land cover change. Originally the land contained vast open forests and savannahs, which European settlers took advantage of for timber and agriculture. By the 1920s, the land had been overused and depleted, leading to the abandonment of the unusable farmland. The Southeast experienced a time of declining agriculture during this period; it wasn't until the 1950s and 1960s when the timber industry recovered, and it has been steadily growing since (Sohl).

Understanding the effects of this deforestation-reforestation trend in the Southeast is important for the possible linkage to the warming hole. Land cover changes affects temperature, soil moisture, albedo, leaf area index, and other meteorological parameters that play important roles in both weather and climate. Understanding these climatic changes is of growing concern because these changes are not only affecting local and regional areas but also have consequences on the global scale (Trail).

Studies in this area have used both modeling and observational techniques to obtain their data. One model-based study compared two southeastern U.S. land use/land cover change scenarios to the current land use/cover for four seasons of the year 2050. The two scenarios they used were (1) reforestation of cropland and (2) forest to cropland. In the first scenario, they found that reforestation of crops in Southeast U.S. led to warming due to increased stomatal resistance and hence, decreased transpiration, and decreased albedo. However, they found that the increased surface roughness led to more energy being transferred as latent heat rather than sensible heat, which may offset the degree of warming of the reforested cropland. In the second scenario, they found that cooling tends to occur when forest is replaced with cropland in the Southeast U.S. They found that in the winter, the cooling was mainly due to increased albedo; while in the spring and summer, the cooling was driven both by increased albedo and decreased stomatal resistance. All seasons showed a decrease in stomatal resistance and surface roughness, however (Trail).

An observational study looked at how forest regrowth in the North Carolina Piedmont changed runoff, which is directly affected by water consumption as a form of evapotranspiration (Kim). They used observational data from two watersheds that underwent reforestation from farmland, and a watershed that had consistent forest cover over the same time period as a comparison. They found that increasing forestland led to increased water consumption and evapotranspiration due to the fact that forests intercept more precipitation and transpire at a greater rate and for a longer period than crops (Kim). The higher rate of evapotranspiration hints at decreasing temperatures for the reforested area.

Overall, the general agreement has been that reforestation decreases near-surface temperature due to increases in latent heat, leaf area index, and roughness length (Mahmood). Vegetation can also help reduce the amount of CO_2 in the atmosphere, leading to decreased temperatures. However, it can be seen that the two previously described studies led to opposite conclusions on evapotranspiration, which has a direct effect on near-surface temperature. This shows that taking a closer look at the Southeast U.S. specifically is necessary in order to determine how reforestation affects the region. In addition, isolating the role of land cover in past temperature changes helps to better understand what other climate drivers did or did not do.

Based on previous studies, the expected result is that increasing amounts of forestland will reduce temperatures in the Southeast region. However, the effects of reforestation may alter other meteorological parameters that offset the cooling effect. In addition, while the overall effect is expected to decrease temperatures in the region, local effects may vary. For instance, as a whole, some states may have experienced abundant reforestation, while others may have experienced deforestation. Some states may have also experienced a time of increased precipitation, while others may have undergone a period of suppressed precipitation. These other effects are beyond the scope of this study. By analyzing temperature effects, a correlation between reforestation and temperature can be found. If a negative correlation between the two parameters is found, reforestation may be accepted as a contributor to the Southeast warming hole.

CHAPTER II

METHODS

Study area

The warming hole constitutes the majority of the states that are considered to be the Southeast region of the United States: Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, and Tennessee. However, as shown in Figure 1, the warming hole extends to other areas as well. In order to receive the best results, this study includes the eight states listed above, as well as Arkansas, Louisiana, Oklahoma, and East Texas (east of a Dallas-Fort Worth and Victoria line). This region encompasses the naturally forested areas of the southeastern U.S. and includes the portion of the Southeast that has experienced "suppressed" warming.

Temperature data

Temperature values were obtained from NOAA's NCDC (National Climatic Data Center) dataset, which extracted the information from their GHCND (Global Historical Climatology Network) database. Their "Monthly Summaries" are derived from the GHCN-Daily database, which is "a composite of climate records from numerous sources that were merged and then subjected to a suite of quality assurance reviews" (NOAA).

Using NOAA's NCDC database, the monthly mean minimum and maximum temperatures were obtained for the decades of the 1930s, 1960s, and 1990s for all stations in each of the twelve states. As long as a station contained 90% of the temperature data for a particular decade, it was included in the study; if not, it was thrown out. There ended up being a total of 476 stations for the 1930s, 901 for the 1960s, and 904 for the 1990s that met this criterion. However, in order to compare on a station-by-station basis, only stations that were in both the 1930s and 1960s were used for the comparison of those decades, and stations that were both in the 1960s and 1990s were used for the comparison of those decades; this left 330 stations for the 1930s-1960s (early period) comparison and 600 stations for the 1960s-1990s (late period) comparison. The 600 stations in the late period do not include the stations in the 10% of counties with the greatest population for the 1960s-1990s comparison in order to exclude any bias from urbanized cities. After obtaining all suitable stations, the minimum and maximum temperatures for each month were averaged for every station in each of the three decades, giving the decadal mean minimum and maximum temperatures by month for all of the stations. Once every station had monthly minimum and maximum temperature averages, the climate monthly normals (1971-2000) were recorded for each of them. The climate normals were obtained from Golden Gate Weather Services and NCDC. The use of the normals warrants the departure of temperatures from "the norm" to be seen. In order to find this departure, the mean minimum and maximum temperatures were subtracted from the normal minimum and maximum, respectively, for each month of every station. Since the difference of temperatures for each month for every station of the three decades has been calculated, this difference (positive being warmer than the norm, negative being cooler) can then be compared to the forestland fraction to see if there is a significant relationship between the two.

Forestland cover data

USGS Land Cover Institute (LCI) created a time series dataset of cropland proportions by county in order to illustrate land use conversion and rates of change. This set is compiled of cropland data from 1850 to the present; it records "improved farmland" acres for certain years from 1850 to 1920. The land cover data for the years 1930 and 1940 were averaged for the 1930s; the 1964 land cover data was used for the 1960s; and land cover data for the years 1992 and 1997 were averaged for the 1990s. The ratio of area of improved farmland/cropland to total country area was recorded for the 1930s, 1960s, and 1990s; by subtracting this value from 1, the fraction of forested land cover was produced.

After obtaining the forestland fraction for each of the stations for the three decades, the forestland fraction change was found for the early and late periods. This was achieved simply by taking the difference in forestland fraction between the 1930s and 1960s for the early period comparison and between the 1960s and 1990s for the late period comparison.

After both the temperature change and the reforestation fraction for the early and late periods were documented, region-wide and statewide analyses for the summer (June-August, JJA) and winter (December-February, DJF) seasons were performed.

CHAPTER III

RESULTS

All stations' minimum and maximum temperature changes in both seasons were plotted against their respective forestland change ('reforestation fraction') for the 1930s-1960s (early period) and the 1960s-1990s (late period); these are shown in Figures 3 and 4, respectively. The main trend that sticks out with these graphs is that the early period was a time of cooling and the late period was a time of warming. The majority of the points being on the negative y-axis for the early period and on the positive y-axis for the late period show this.

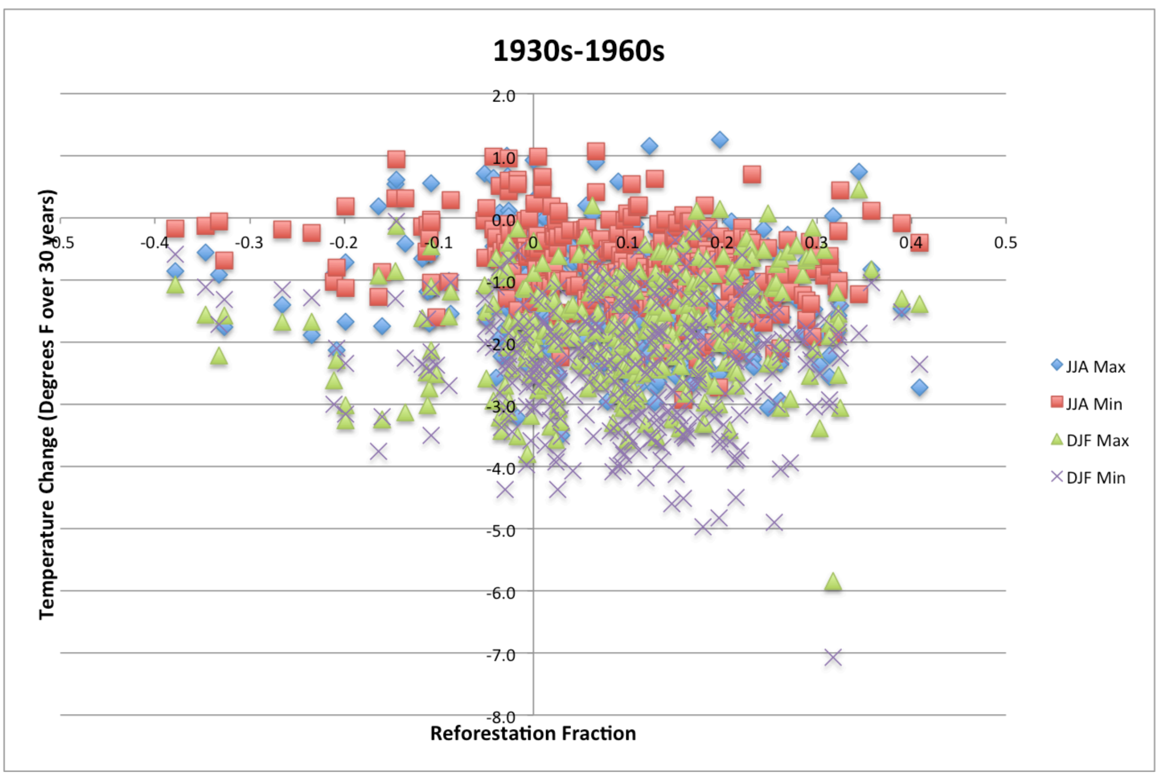

Figure 3. Temperature change and forestland change from the 1930s to 1960s in the S Southeast U.S. This figure shows the JJA and DJF maximum and minimum temperatures plotted against the corresponding reforestation fraction.

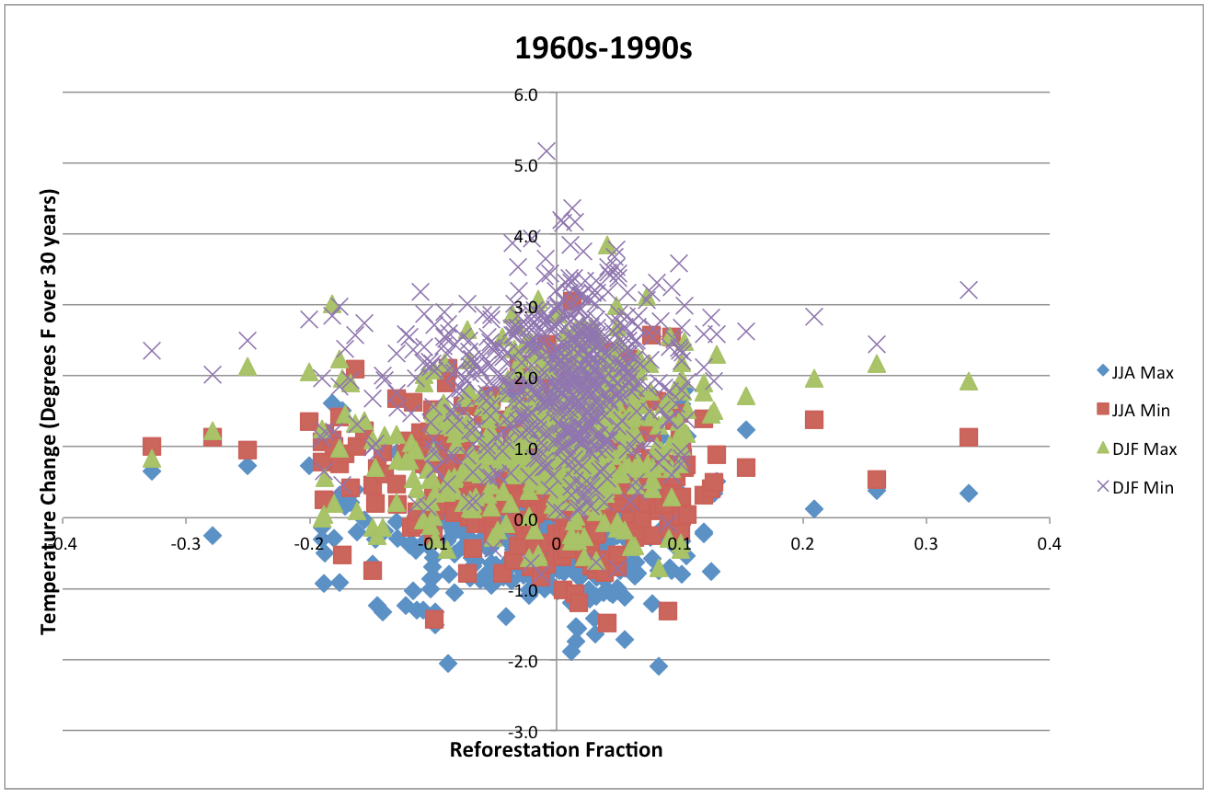

Figure 4. Temperature change and forestland change from the 1960s to 1990s in the Southeast U.S. This figure shows the JJA and DJF maximum and minimum temperatures plotted against the corresponding reforestation fraction.

In order to reduce noise and allow trends to become more prominent, an analysis of the average temperature change versus reforestation fraction was computed for both periods. The 330 stations shared by the early period and the 600 stations shared by the late period were organized by increasing reforestation fraction and then split into 10 equal groups – each group containing 33 stations for the early period and 60 stations for the late period. The reforestation fraction and temperature change data from each of these groups were averaged for JJA min, JJA max, DJF min, and DJF max, creating 10 points for each category, as shown in Figures 5 and 6.

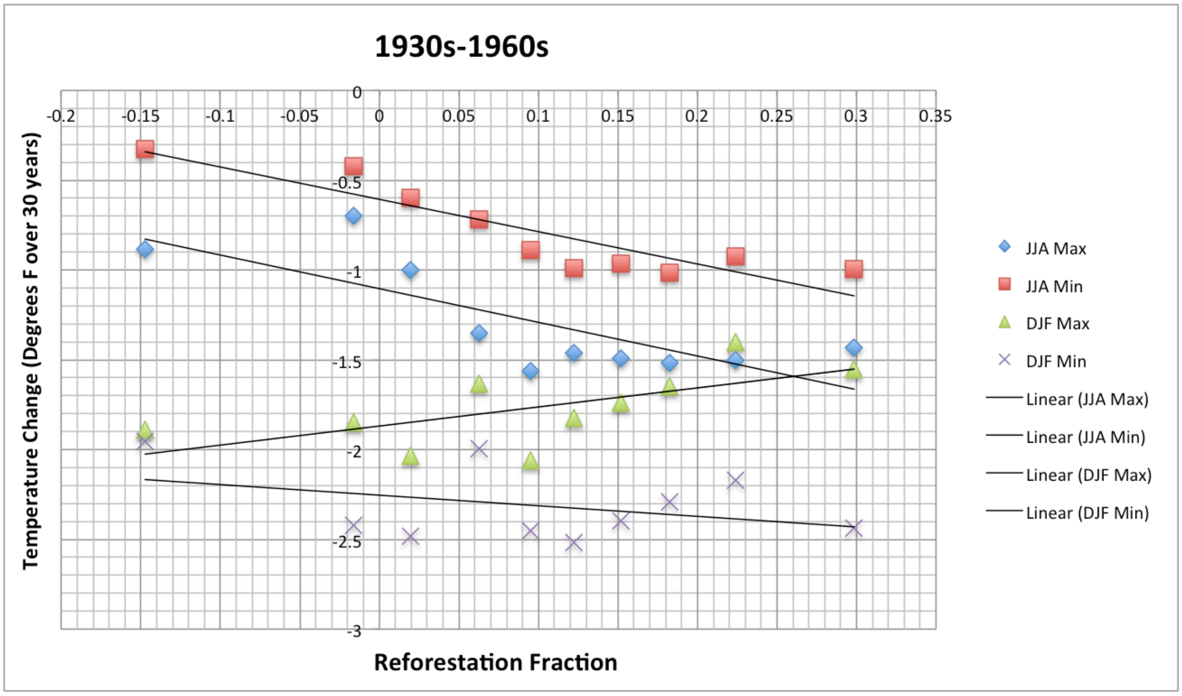

Figure 5. Average temperature change and forestland change from the 1930s to 1960s in the Southeast U.S. This figure shows the JJA and DJF maximum and minimum temperature averages plotted against the corresponding average reforestation fraction.

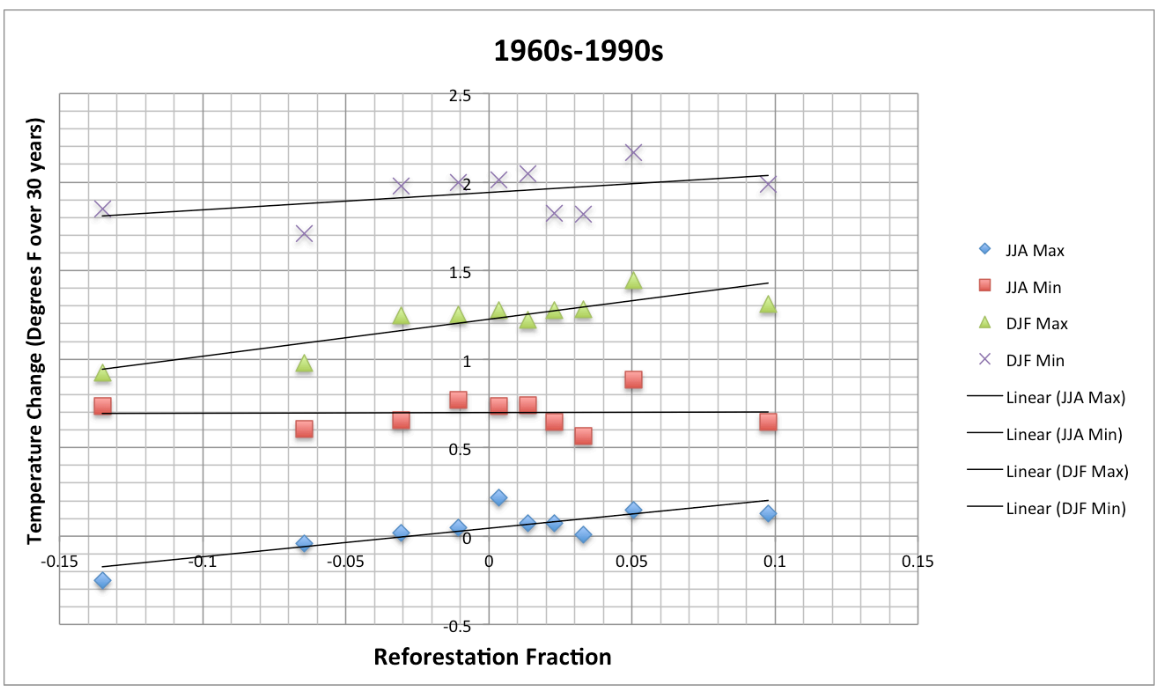

Figure 6. Average temperature change and forestland change from the 1960s to 1990s in the Southeast U.S. This figure shows the JJA and DJF maximum and minimum temperature averages plotted against the corresponding average reforestation fraction.

The same general trends appear in Figures 5 and 6 that were shown in Figures 3 and 4 – the early period was a time of cooling and the later period was a time of warming. However, taking a closer look, it appears that the early period experiences more cooling with more reforestation, whereas the later period lacks evidence of any reforestation effect.

In order to see if there is a difference between region-wide and statewide trends, the early and late periods were split up by state and organized into 'more reforestation' vs. 'less reforestation' categories for each state and period. This isolates changes within each state and eliminates the possible confounding effect of large-scale natural variability.

Table 1 summarizes the data for the 'more reforestation' and 'less reforestation' categories for both the early and late periods. The numbers represent how often stations in a reforestation category recorded more warming (or less cooling) than stations in the opposite reforestation category. For minimum temperatures, in both seasons and periods, the vast majority of states feature more warming with less reforestation. The summer maximum shows a similar effect as the minimum temperatures in the early period, but does not display any effect for the later period. The winter maximum does not exhibit any effect for either period.

Table 1. Number of states experiencing more warming with 'more reforestation' and 'less reforestation.'

Category with more warming	1930-1960 'less reforestation'	1930-1960 'more reforestation'	1960-1990 'less reforestation'	1960-1990 'more reforestation"
JJA Max	10	2	6	6
JJA Min	10	2	9	3
DJF Max	5	7	5	7
DJF Min	10	2	9	3

Graphs were created to visually display the information in Table 1 (Figures 7-10). At first glance, the graphs show the same relationship as the previous graphs: the early period experiences cooling, with more cooling with more reforestation; and the late period experiences warming with no apparent reforestation effect. However, the lines on these graphs are connecting pairs of points that represent the 'more reforestation' and the 'less reforestation' for each state. A majority of these lines show a negative slope, as seen already in Table 1, suggesting that most of the states experience more warming with less reforestation and less warming with more reforestation in most cases.

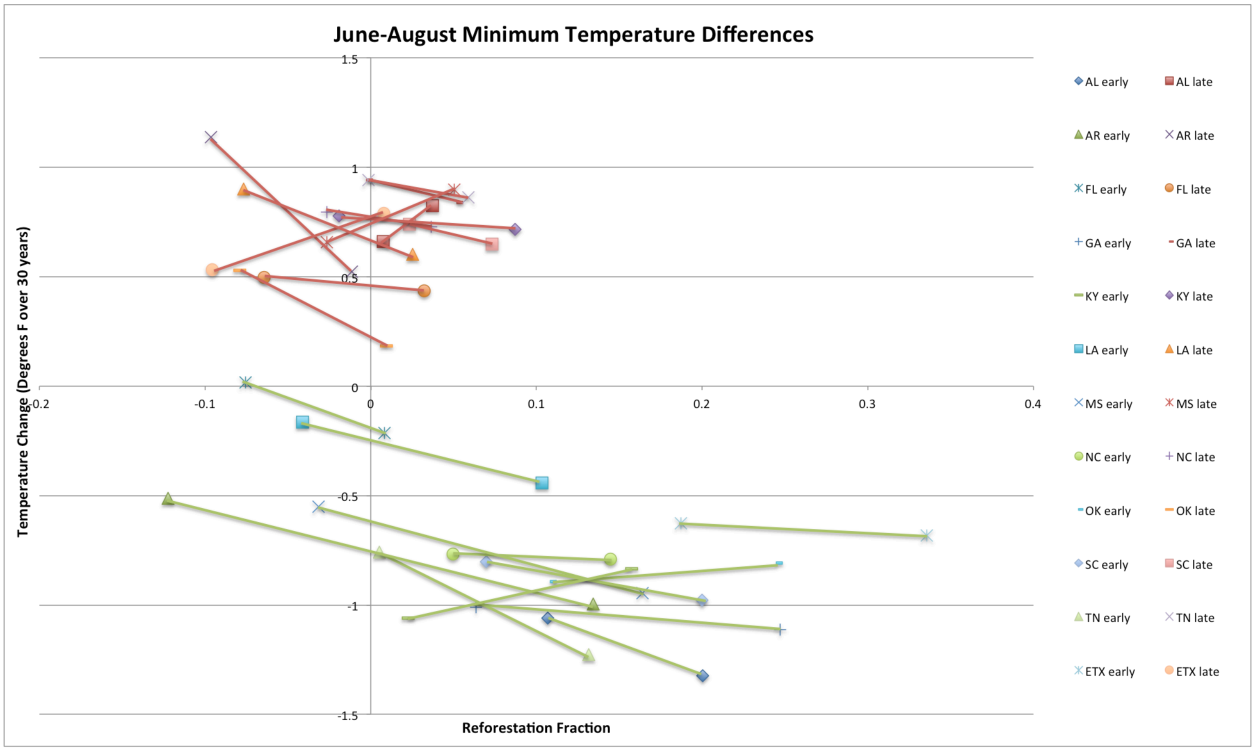

Figure 7. JJA minimum by state. Statewide analysis of 'more reforestation' vs. 'less reforestation' in both the early period (green) and the late period (red) for summer minimum temperatures.

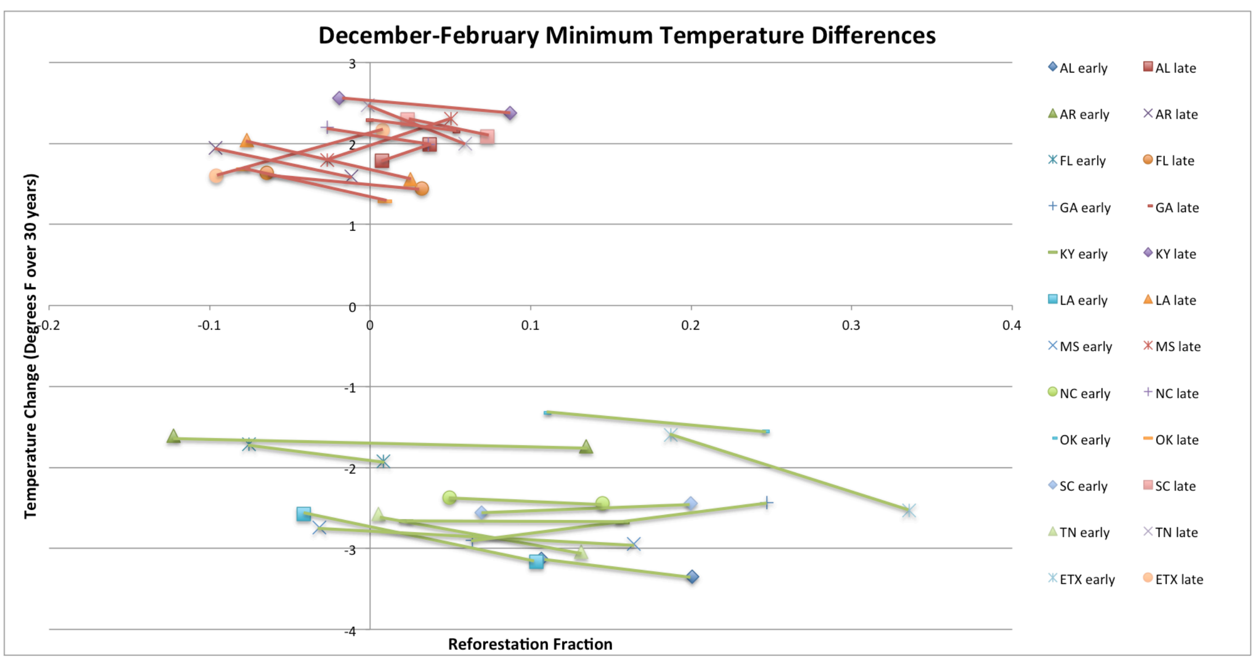

Figure 8. DJF minimum by state. Statewide analysis of 'more reforestation' vs. 'less reforestation' in both the early period (green) and the late period (red) for winter minimum temperatures.

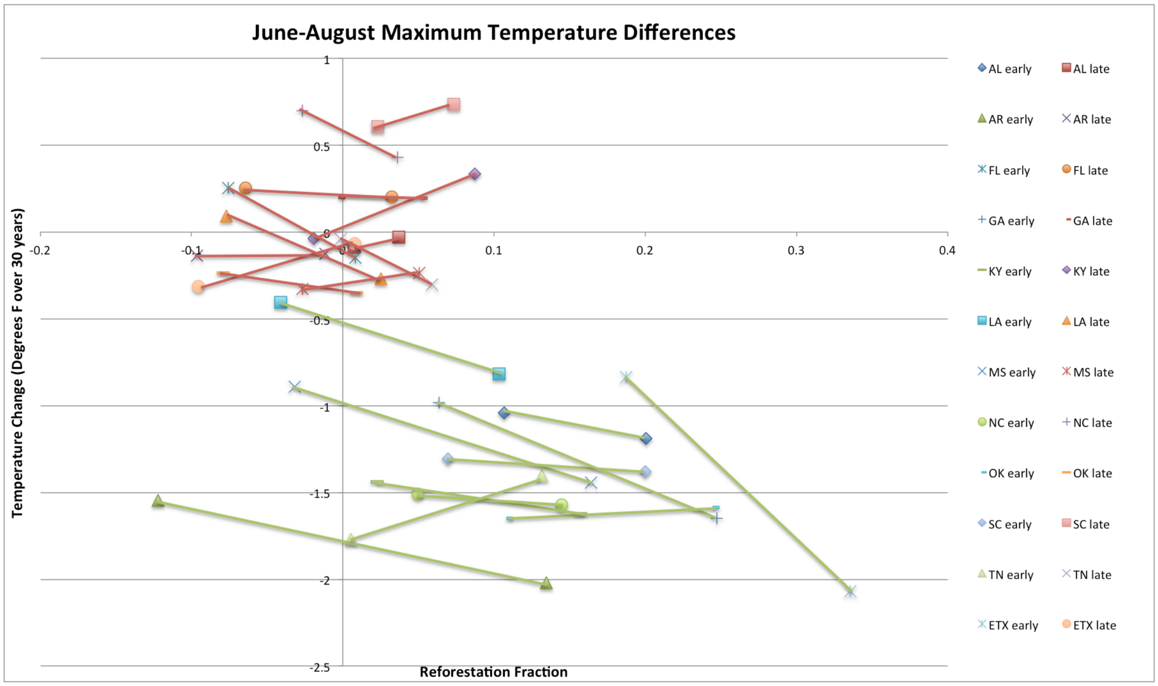

Figure 9. JJA maximum by state. Statewide analysis of 'more reforestation' vs. 'less reforestation' in both the early period (green) and the late period (red) for summer maximum temperatures.

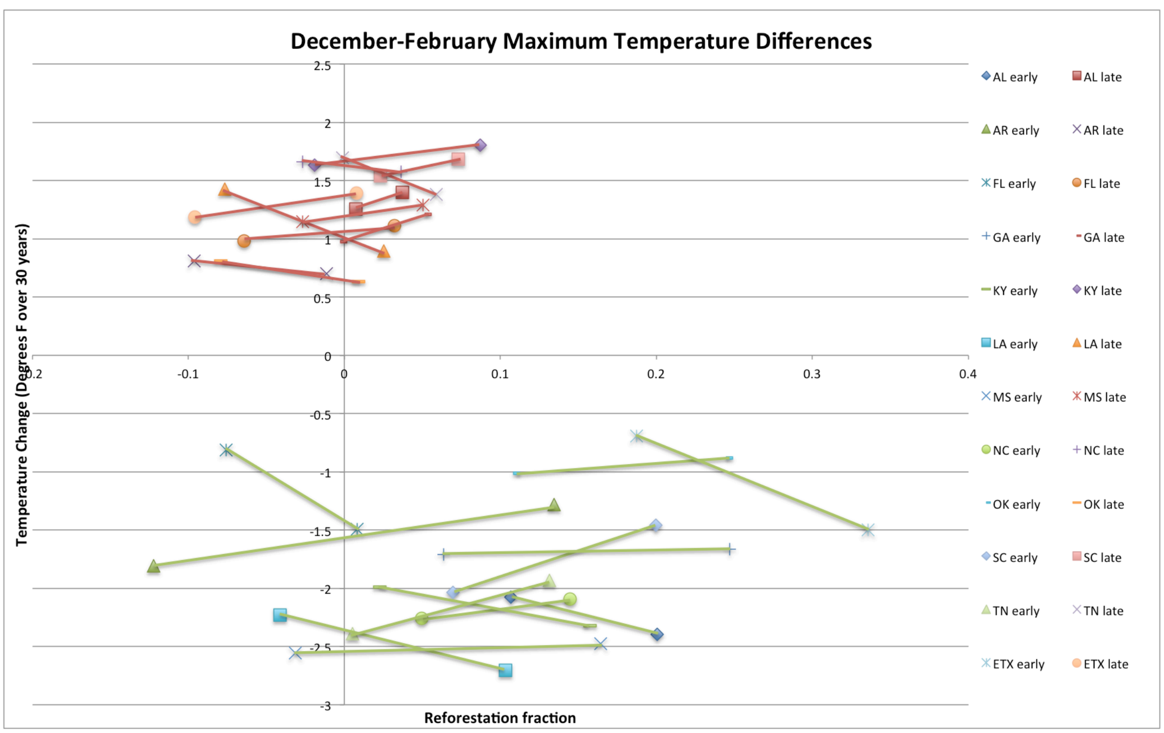

Figure 10. DJF maximum by state. Statewide analysis of 'more reforestation' vs. 'less reforestation' in both the early period (green) and the late period (red) for winter maximum temperatures.

Statistical one-sample t-tests were executed in order to see if the sample mean of the state-specific slopes are significantly different than zero. The slopes from each state for JJA min, JJA max, DJF min, and DJF max for both the early and late periods were tested. The formula used is:

$$t = \frac{\bar{x} - \mu_0}{s/\sqrt{n}};$$

where $\bar{x}$ is the mean of the slopes in each season and time period, μ_0 is zero, s is the standard deviation of the slopes, and n is the sample size – 12 (one slope for each state).

Using 0.05 as the level of significance, the results of the one-sample t-tests showed that JJA min, JJA max, and DJF min slopes were all significantly different from zero for the early period, with DJF max proving to not be significant; while none of the slopes proved to be significantly different from zero for the late period.

The same test was run using an aggregation of the data. For each state and period, the JJA min, JJA max, DJF min, and DJF max slopes were averaged to make up the sample. Running a one-sample t-test for each period concluded that the slopes of the early period are significantly different from zero, while the slopes of the late period are not.

Paired t-tests were run for each of these scenarios as well, showing the same results as the one-sample t-tests. However, another statistical test was run to see if the slopes of the early period are significantly different from the slopes of the late period; with the results concluding that with a 0.05 significance level, the slopes of the two periods are not significantly different from each other. A reason the late period slopes calculated to be insignificant may be due to the smaller difference between the ‘more reforestation’ and ‘less reforestation’ points. Since the late period experienced a lesser amount of reforestation, there was more room for noise to have an effect.

Since there is a lack of significant difference in slopes between the early and late periods, it is implied that the two sets of slopes can be treated as samples from the same population; therefore, another statistical test was run combining the data across the decades. The JJA min, JJA max, DJF min, and DJF max slopes collectively (both early and late period slopes) were tested to see if they had a mean that is significantly different from zero. The slopes proved to be significantly different from zero for all but DJF max.

CHAPTER IV

CONCLUSIONS

The regional analysis showed that the 1930s-1960s was a time of cooling with more cooling with more reforestation, and that the 1960s-1990s was a time of warming with no apparent reforestation effect. However, the state-by-state analysis shows that for both the early and late periods, more reforestation is coupled with more cooling (less warming). For minimum temperatures, in both seasons and periods, the vast majority of the states feature more warming with less reforestation. The summer maximum shows a similar effect as the minimum temperatures in the early period, but does not display any effect for the later period. The winter maximum does not exhibit any effect for either period.

Based on the results showing that reforestation tends to have a cooling effect on temperature, this study is consistent with the observational study that looked at forest regrowth in the North Carolina Piedmont described earlier. This leads to the conclusion that increasing forestland leads to increased evapotranspiration, which has a cooling effect on surface temperatures (Kim, Trail). This increase may be a direct cause of the larger leaf area index, causing more precipitation to be intercepted and transpired (Kim).

Taking median slope values of minimum and maximum temperatures, the overall apparent effect of reforestation on local temperatures is about -0.18 °C per 10% increase in forest fraction for minimum temperatures and is near 0 °C per 10% increase in forest fraction for maximum temperatures. Given an overall regional reforestation of about 12%, using the county-scale effect to estimate the regional effect, the net overall effect on temperatures is -0.11 °C. This is a lower bound on the magnitude of the reforestation effect; the overall region-wide effect on temperatures cannot be estimated using this approach. Reforestation may not be the sole contributor to the Southeast warming hole, but it is a significant factor.

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